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COLD REGIONS AIR POLLUTION BIBLIOGRAPHY AND SUMMARY

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16. ABSTRACT

Through a series of workshops on cold climate environmental research priorities, conducted in 1982 by Battelle for the Environmental Protection Agency and the Department of Energy, air pollution was identified as the topic of highest priority. The current state of knowledge on air pollution in cold climates was considered to be widely scattered in the published and "gray"scientific literature. One of the high priority projects of air pollution research was therefore identified to be the compilation of a bibliography and synthesis of what is known and what is not known about air pollution in the cold regions. This document is the result of that recommendation. The bibliography on air pollution compiled for these "cold regions' includes papers on the sources, species, concentrations, pathways, and effects of various kinds of air pollution, including phenomena such as ice fog, and arctic haze which are peculiar to the region.. Most of the listed references apply to Alaska; Fairbanks in particular, is strongly represented in the literature on ice fog, carbon monoxide, automobile emissions, and other topics. The references on arctic haze, a phenomenon which pervades the entire Arctic Basin, are fairly extensive as are references from northern Europe on haze, acid rain, and other pollution problems.

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ABSTRACT

Through a series of workshops on cold climate environmental research priorities, conducted in 1982 by Battelle for the Environmental Protection Agency and the Department of Energy, air pollution was identified as the topic of highest priority. The current state of knowledge on air pollution in cold climates was considered to be incomplete, and available information was believed to be widely scattered in the published and "gray" scientific literature. One of the high priority projects of air pollution research was therefore identified to be the compilation of a bibliography and synthesis of what is known and what is not known about air pollution in the cold regions.

This document is the result of that recommendation. It was prepared by the Geophysical Institute of the University of Alaska under Subcontract No. B-A3543-A-U to the Pacific Northwest Labortory (PNL) of Battelle Memorial Institute. PNL manages the Cold Climate Environmental Research Program as an agent of the Department of Energy through DOE's interagency agreement (No. DW 89930699-01-0) with the Corvallis Environmental Research Laboratory of the U.S. Environmental Protection Agency. The "cold regions" referred to in this document are defined as the arctic and sub-arctic areas roughly north of 60°N latitude. This includes most of Alaska, northern Canada (particularly the Yukon and Northwest Territories), northern Europe, Siberia, and the Arctic Ocean.

The bibliography on air pollution compiled for these "cold regions" includes papers on the sources, species, concentrations, pathways, and effects of various kinds of air pollution, including phenomena such as ice fog and arctic haze which are peculiar to the region. Most of the listed references apply to Alaska; Fairbanks in particularly is strongly represented in the literature on ice fog, carbon monoxide, automobile emissions, and other topics. The references on arctic haze, a phenomenon which pervades the entire Arctic Basin, are fairly extensive as are references from northern Europe on haze, acid rain, and other pollution problems. The smallest number of papers comes from northern Canada and the Soviet Union. The considerable literature on pollution in southern Canada (Toronto, Ottawa, etc.) was not included because it did not come under our definition of "cold regions." Soviet literature, if it exists, does not appear to be available in translation, as indicated by our computer and other searches.

Availability of the Listed References

Many of the listed references are "grey literature", i.e., they are reports which have not been published or extensively distributed. Microfiches of these reports which are otherwise difficult to obtain (marked (M) on each reference) are at the following locations:

Library, Geophysical Institute, University of Alaska,
Fairbanks, AK 99701

Alaska Resources Library, Federal Building, 701 C Street,
Box 36, Anchorage, AK 99513

Library, Arctic Environmental Information and Data Center,
707 A Street, Anchorage, AK 99501

Copies of noncopyrighted material may be obtained at the cost of reproducing them at these location.

A more comprehensive document which includes the abstracts of all the papers listed below has been published by the Geophysical Institute, University of Alaska as Report UAG R No. 298 and is available from the Institute at no cost.

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I. SUMMARY

This section attempts to summarize and synthesize the available information (contained in the bibliography of Section II of this report) on the various aspects of air pollution in the cold regions. Information gaps are identified and recommendations on further research are made. It should be stressed that the recommendations are intended to fill present data and information gaps, regardless of the cost involved or the relation of the recommended research to the missions of EPA or DOE in reducing pollution. Research priorities for these agencies have recently been established (J. B. States, 1983, Assessment of Cold-Climate Environmental Research Priorities, Battelle PNL-4581, 50 pp.).

CHARACTERISTICS OF COLD REGIONS AIR POLLUTION

Problems of air pollution in high latitudes, especially during winter, have attracted ever increasing attention during the past two decades, (Benson, 1965, Benson, Bowling and Weller, 1983). Winter air masses become very stable and tend to stagnate to the extent that air quality problems exist throughout northern Canada, Siberia, Scandinavia, and Alaska.

As seasonal temperature decreases in the northern cities of these regions the need for increased heat and power causes an increase in all sources of pollution. Unfortunately, it is in these times that the stability of the air mass becomes most extreme (Bilello, 1966). Thus, natural and man-made factors reinforce one another in ways which invariably lead to intensification, never mitigation, of the air pollution problem (Benson, 1970).

In addition, during winter, water becomes a component of the air pollution because it condenses into tiny droplets and/or crystals even when the quantity involved is quite small (air at +20°C can hold about 250 times more water vapor than air at -40°C). At temperatures below -35° to -40°C ice fog is produced which severely restricts visibility but also serves as an indicator that man-made pollutants are present (Benson, 1970, Ohtake, 1970).

Air pollution problems in the North can be severe, as illustrated by the air quality of the Fairbanks air shed, which is unique for several interrelated reasons stemming from the extreme stability of the air mass and its tendency to stagnate. Indeed, a special stability class "Pasquill G" was established to describe extreme cases like the Fairbanks air shed.

The air mass is so stable that the per capita air pollution is 10 to 100 times greater than in the Los Angeles area. This statement is based on the observation that levels of carbon monoxide, and total hydrocarbons measured in Fairbanks (Jenkins, et al., 1975), are comparable to values measured in Los Angeles, New York and Detroit where populations are much higher. The national ambient air quality standards for carbon monoxide are, in fact, frequently exceeded in Fairbanks (see p. 31).

The problems of air chemistry have generally been studied in temperate latitudes and mostly at high temperatures. The Los Angeles problems quickly come to mind as being at the opposite end of the spectrum from Fairbanks problems (Table 1). The problems in Los Angeles stem from automobile exhaust and industrial chemicals which are cooked in the intense sunlight and form photochemical smog, characterized by products of oxidation (O_3, etc.). To have this occur, high temperatures, lots of sunlight, water vapor (for OH and O_2H radicals) as well as plenty of hydrocarbon and NO_x sources are required. In Fairbanks, we have low temperatures, and almost no sunlight (less than 6 hours per day for 70 days, and less than 4 hours per day for 25 days). Therefore, even though significant hydrocarbon concentrations are present (Jenkins et al., 1975), we do not expect photochemical reactions to be important in winter although this may become a problem in summer because of the many hours of sunlight. In winter a different mix of pollutants become trapped in the surface inversion layer. Because of the snow cover, natural aerosols are at a minimum, and only those from combustion of coal, oil, natural gas and wood are present; they interact with an abundant supply of ice crystals and supercooled water droplets (Benson, 1970, Ohtake, 1970).

TABLE 1

SPECTRUM OF AIR POLLUTION SETTINGS

(showing the two end members)

	Fairbanks in Winter Low Temperature Icefog/Pollution	Los Angeles in Summer Smog
Temperature		
Temp Inversions	30°C/100m (Surface)	10°C/100m (Above Ground)
Radiation	None during winter (~980 W m^{-2} at the summer solstice)	High (>1000 W m^{-2})
Saturation Vapor Pressure	Low (0.05 mb at -50°C)	High (42.43 mb at 30°C)
Chemistry	Reducing atmosphere No photochemical reaction "Wet" air chemistry (Low absolute water content but condensed form present)	Oxidizing atmosphere Max. photochemical reaction "Dry" air chemistry (High absolute water content but condensed form absent)

The main questions to be answered deal with the nature and effects of this interaction between ice crystals, or super-cooled water droplets and combustion aerosols and gases. What is the physical state of the fog particles, supercooled droplets or ice crystals, as a function of temperature and different pollutant levels? Do the pollutants cause more nucleation of smaller ice crystals and thicker ice fog? Are pollutants selectively removed from the air by the fogs due to their physical and chemical interaction? Are the "inert" gases such as CO and CO_2 incorporated into the ice crystals? How do the reactive gases SO_2, NO, NO_x and O_3 behave relative to each other and is their conversion to $SO_4^=$, NO_3^- and O_2 enhanced or decreased by ice fog? Do ice crystals in the respirable size range trap contaminants and actively transport them into the lungs? Are certain particle size ranges removed preferentially by ice crystals, or are they responsible for the enhancement of ice fog? How will hydrocarbons affect the growth and dissipation of ice fogs; do they form hydrophobic layers on crystals? What different effects are observed when power plant emissions are mixed downward into the lower air mass, compared with the more normal case when they remain aloft?

These questions need to be answered before we will have enough information to begin to understand the implication of increased development in cold climates. Several studies on the concentrations of specific pollutants have been carried out in the Fairbanks area including:

(i) Winchester, et al., (1967): lead and halogens

(ii) Kumai, (1964); Ohtake, (1970): chemical composition of ice fog nuclei

(iii) Holty, (1973): lead, oxides of nitrogen, CO, $SO_4^=$, NH_4^+, Cl^-

(iv) Jenkins, et al., (1975): total hydrocarbons, CO, CO_2, NO_x

(v) Coutts, (1979): NO - NO_2 - O_3 interactions

(vi) Reichardt and Reidy, (1980): polycyclic aromatic hydrocarbons (PAH).

Information of this kind for other northern cities is much less complete or totally absent (see also section on monitoring). With trends towards accelerated exploitation of arctic resources it becomes increasingly important to know the effects of growth on an area so that corrective steps can be taken. Some of these corrective steps are discussed in later sections.

Recommendations for Further Research

Enough information has already been gathered to date to point out some broad problem areas. In very general terms, the most important gaps in our knowledge will require research in the following areas:

1. A detailed study of low temperature air chemistry in the presence of fogs consisting of supercooled water droplets and/or ice crystals.
2. An integrated study of the structure, dynamics and time history of the very stable winter atmosphere and the diffusion processes which affect its atmospheric pollutants.

These recommendations will be discussed in greater detail in the following sections.

THE CHEMICAL NATURE OF COLD REGIONS AIR POLLUTION

The chemistry of air pollution in cold climates is quite different from that at lower latitudes, as shown in the preceding section. The photochemical smog typical of Los Angeles does not exist in Fairbanks, but there are reports (e.g. Schjoldager et al., 1978 , and Bottenheim and Strausz, 1980), that photochemical activity could occur in the Arctic, particularly during the summer solstice. Schjoldager (1954), indicates that local production of ozone occurs in Norway. Peake and Sandhu (1983), have shown that another photochemical product, PAN (peroxyacetyl nitrate), is produced in winter in Alberta at about 25% of the summer level. An interesting paper on photochemical mechanism for high latitudes is the one by Bottenheim and Strausz. Other photochemical papers are by Schjoldager et al. (1978, and 1979), (see also Monitoring section for more comments about ozone, p. 39).

More exotic pollution products may be present in large quantities in northern cities. Reichardt and Reidy (1980) for example, demonstrated that polycyclic aromatic hydrocarbons (PAH) concentrations in Fairbanks under strong winter inversions can be equal to those of large urban areas of the world. This study occurred before the recent increased use of wood stoves. Daisey et al. (1981) showed that PAH material in remote areas of the Arctic are within an order of magnitude of concentrations found in large urban areas.

There is a fairly large body of literature on various trace elements, all pointing to long range transport of anthropogenic pollution from low latitudes into the Arctic (see the section on Arctic haze, p. 25).

Rasmussen et al., (1982), show that carbon monoxide is enriched in snow as compared to methane; this finding is of greater interest in long range research, however, than in urban pollution studies (see monitoring section for other remarks about CO, p. 36). Cavanaugh et al., (1969), show startlingly high n-butanol concentrations in arctic air (~ 0.1 ppm) which do not appear to be an experimental artifact.

The report by McCandless (1982), on Whitehorse urban air problems confirms the growing evidence for the significant woodsmoke contribution to both TSP and PAH levels. Formaldehyde in ice fog samples are high (0.5 - 1.16 $\mu g\ ml^{-1}$) presumably due to combustion, as reported by Grosjean and Wright (1983). Formate and acetate are found in precipitation (Galloway et al., 1982) in Alaska in normal quantities.

The pH records of precipitation in Alaska's remote areas tend to be normal to slightly acid (~ 6.3 down to 4.7; NADP, 1983, Galloway et al., 1982). The most unusual pH conditions have been found within the city of Fairbanks during winter. The pH of ice fog and snow on the ground can go as high as 10.2 (presumably due to metal oxide ash fall-out from woodstoves, and possibly from power plants; (Gosink, 1981, 1983; Grosjean and Wright, 1983).

A discussion of the concentrations of the more common chemical compounds and elements present in the polluted air masses of northern latitudes is contained in the section on monitoring (p. 36).

Gaps in the Technical Literature

We have no data on indoor air pollution in the cold regions. This aspect of air pollution studies is just beginning, so the gap is under-

standable. It is anticipated that the only unusual features may deal with aspects of air exchange with the outside. Many homes are being insulated more carefully and made airtight.

Photochemical data for ~ 70°N are missing. The only papers available are for 60°N and farther south.

Power plant emission data are incomplete, but it is not certain that there will be any unusual features in the cold regions as opposed to what is already known about emissions at lower latitudes.

Air pollution data for the vast Soviet sector of the Arctic and Subarctic are almost entirely missing. As noted in the preface, such papers, if they exist, do not appear to be available in translation. An exception is the paper by Morachevsky et al.

Recommendations for Further Research

The following topics need to be addressed in future studies:

1. Indoor air pollution:
   (a) possible trapping of pollutants inside by overly tight construction and/or lack of ventilation,
   (b) transfer of pollutants from polluted urban air to the inside.
   (c) dependence of indoor pollution on height of inlet air vents in tall buildings.
2. Photochemistry at high latitudes:
   (a) ultraviolet radiation,
   (b) ozone and PAH data for clean and dirty sites at all times of the year,
   (c) information about hydroxy and peroxy free radicals.
   (d) oxidation of NO, SO_2 etc.

3. Particulate matter:
   (a) the mass loading, numbers and size distribution of particulates,
   (b) chemical information about possible selective partitioning of pollutants on the different size ranges of pollutants,
   (c) The scavenging efficiency of snow and ice fog.
4. A statistical study of health records for the months of January and July for eye and respiratory disease. (This should discriminate between people living and working in polluted urban areas versus people who spend part of their time in polluted areas and those who remain outside the polluted urban centers).
5. More chemical and biological data about carcinogenic factors in urban pollutants.
6. More chemical details about the pollutants trapped in snow and their potential for pollution of streams during thaw.

METEOROLOGY OF COLD REGIONS AIR POLLUTION

High latitude air pollution is principally a cold-season phenomenon, and is due directly to the extreme stability of the air at high latitudes in winter (Bowling, 1984). This stability is in turn a result of the solar radiation regime. At 60° North, for instance, the true solar elevation angle at noon at the winter solstice is only 6° 33' and the day is only 5 hours and 52 minutes long, which allows almost no solar heating. (This noon solar elevation corresponds to a solar elevation of less than forty minutes after sunrise in Los Angeles.) At 68° N, the sun no longer rises at all at the winter solstice. The result is that nighttime radiation conditions extend throughout the part of the day with maximum pollutant emissions. Mixing heights as low as 6 m have been measured in downtown Fairbanks.

Inversions

A typical high-latitude inversion differs substantially from those responsible for air pollution problems in locations such as Los Angeles (Benson, 1970). In a Los Angeles-type (or elevated) inversion, the temperature normally decreases with height for the first few hundred meters above the ground, then increases rather sharply in a layer known as a capping inversion. An inversion of this type may be due to warm air overrunning cold air, to subsidence above a surface layer, or to limited heating from below of a stable air mass. Inversions of this type may occur at high latitudes, but it is rare for them to be associated with episodes of poor air quality (Bowling, 1983). High pollutant levels occur with surface-based inversions, i.e., those in which the temperature increases from the ground up. The maximum temperature in an

Alaskan sounding is frequently as much as 2 km above the surface, and ground temperatures may be only a few degrees higher than those at the tropopause (Bowling, 1967).

Surface inversions are common world-wide on clear, calm nights, and are often referred to as nocturnal inversions. These inversions, however, are normally broken by solar heating during the daylight hours when emissions are highest. In Fairbanks, more than 80% of all soundings (2 am and 2 pm) show surface inversions during December and January (Bilello, 1966). Furthermore, some of these inversions are extremely steep--lapse rates of -10°/100m are common, and value as high as -30°/100 have been recorded over the first 30m (Wendler and Nicpon, 1975; Bowling et al., 1968). The presence of such inversions is readily explained: in the absence of solar heating, the thermal structure near the ground is controlled entirely by long-wave radiation and mechanical turbulence. Long-wave radiation tends to produce an isothermal near-ground lapse rate if dense clouds are present and a steep ground inversion (gradually weakening with elevation) when skies are clear. In exposed areas with substantial pressure gradients, wind-induced turbulence will push these radiative equilibrium states toward the adiabatic. Most high-latitude settlements, however, are located in sheltered areas such as river valleys where wind speeds are often low even with strong regional winds. Furthermore, the clear skies which allow development of inversions are often due to anticyclonic systems with light winds. The observed high frequency of strong surface inversions is the inevitable result.

An elevated inversion allows for a substantial amount of vertical mixing below the inversion "cap", but this is not true of a surface-based

inversion. In a rural area, vertical dispersion of pollutants is due almost entirely to the heat and/or mechanical turbulence associated with pollutant injection. This can be remarkably small: plumes from trucks with exhaust pipes above the cab can frequently be seen to spread in a well-defined layer just above the trailer height (unpublished observation, Bowling). In a town of the size of Fairbanks (population ~ 50,000) there is normally enough heat and traffic-generated turbulence to produce a shallow mixed layer. Just how shallow is indicated by tethered balloon measurements carried out in December 1981 (Bowling, 1983). Rural inversion strengths were on the order of 10°C/100m. Downtown Fairbanks had developed isothermal layers varying from 6 to 30m in depth. Some additional mixing may have been occurring through updrafts along building sides. Since neither inversion strengths nor CO concentrations were extreme for the Fairbanks area, however, it seems unlikely that the true mixing depth on the worst day of an average year would exceed 10m. (In comparison, Los Angeles mixing depths are normally several hundred meters, Benson, 1970.) In addition to affecting the vertical dispersion, the mixing layer is responsible for an intense heat island. Downtown temperatures may be as much as 10° to 14° higher than those in the surrounding rural area (Bowling and Benson, 1978).

Ice fog (section 3) influences the radiative process directly, resulting in greatly weakened inversions or even normal lapse rates within the ice fog, with a relatively steep inversion near the fog top (Benson, 1970; Bowling, 1970). As this will improve vertical mixing, ice fog may be indirectly responsible for reducing CO concentrations. CO emissions may also be lower during ice fog due to diminished traffic and

the almost universal use of preheaters at ice fog temperatures. This may be partly offset, however, by the very large number of unattended cars left idling at -40° and colder. Regardless of the cause, it is an observed fact that CO levels almost never reach violation levels (9ppm) when ice fog is present (Bowling, 1983).

Winds

Winds are important for air pollution both because they carry pollutants away horizontally and because they generate turbulence which weakens the inversion and allows increased vertical dispersion. As already mentioned, the strong ground inversions which are associated with high pollutant levels at high latitudes are normally associated with light winds. Local factors preventing strong winds vary. Anticyclonic conditions are frequent in the Interior of Alaska, and Fairbanks is located in a sheltering arc of hills opening southward into the Tanana Valley. Anchorage is located just west of a sheltering mountain front. The result is that the observed winds during pollution episodes are normally locally generated and therefore light.

Local winds include those generated by cold air drainage, gravity waves, and local-scale eddies, and the interactions of these with regional winds (Benson and Weller, 1970; Bowling and Benson, 1978. From a practical point of view, a more useful division is into winds which produce a net flow through the city (thus removing pollutants) and winds which recirculate pollutants within the city (thus acting to enhance horizontal dispersion). In Fairbanks, the only Alaskan city in which studies have been made of locally generated winds, local drainage wind speeds are of the order of .5 m sec^{-1}, with values up to 1 m sec^{-1}

in well defined channels or on steep slopes. These winds continue through the city under moderate inversion conditions, but under severe inversions the hill slopes may be so much warmer than the valley bottom that the local slope winds may flow out over the dense, cold air mass in the lowest part of the ground inversion (Benson, 1974). Winds measured in the downtown area when CO levels are high may be as low as 10 to 20 cm sec^{-1} (Bowling and Benson, 1978). Gravity drainage winds down major valleys such as the Tanana, Matanuska and Susitna may reach speeds sufficient to break the ground inversion, as has been observed several times on satellite infrared images. Tanana Valley drainage winds at times extend northward far enough to affect the southern part of Fairbanks (including the Weather Service recording station located at the Airport). This situation does not, however, appear to remove pollutants from the downtown area--in fact it has been responsible for several severe (over 15 ppm CO) pollution episodes (Bowling, 1983). One observation has also been made of a long-period (4 hour) seiche oscillation between Fairbanks and Eielson Air Force Base, 50 km away (Bowling and Benson, 1978). This occurred with heavy ice fog and appeared to shift the fog (and the coldest air) back and forth between the two end points rather than actually removing polluted air.

Smaller gravity waves (periods 5-20 minutes) and stationary eddies (such as the one generated over the entire city by the Tanana drainage impinging on the ridge southwest of Fairbanks) produce major spatial and temporal variations in the surface wind field. These are probably responsible for a good deal of horizontal dispersion within the city, but have little or no effect in removing pollutants from the area.

Synoptic Situations Associated with High Latitude Air Pollution Episodes

In all of the high latitude air pollution cases examined so far, clear skies (or very high, cold clouds) and low wind speeds are critical factors. Ice fog in Fairbanks is known to be associated with northerly flow aloft and a surface anticyclone. High CO levels in Fairbanks have not been studied intensively from a synoptic point of view, but one situation well known locally is "chinook" flow. This is not a classical chinook, as the warm winds from the south over the Alaska Range are unable to penetrate the ground inversion, but it is associated with clear skies and temperatures aloft which may be above freezing, while surface temperatures remain below -20° C. Warm air advection just above the surface inversion has been a causative factor in several cases with alert (15 ppm) levels of CO. In Anchorage, the critical factors are high pressure to the north and low pressure well south in the Gulf of Alaska, leading to easterly surface geostrophic flow. The factors determining whether this situation will lead to strong surface winds or stagnation east of the Chugach Range are not well understood at this time (Bowling, 1983).

Modeling

Modeling the air pollution situation at high latitudes is a severe problem. Well-tested standard models generally couple the horizontal and vertical dispersion in such a way that very poor vertical dispersion is associated with very little variability in wind direction. Ground inversions typically show the opposite relationship--Fairbanks winds at a point may vary over 180° or more within half an hour in extreme cases. Furthermore, standard models cannot handle the great spatial variation in winds seen in both Fairbanks and Anchorage. Nevertheless, regulatory agencies

require that standard models be used for environmental impact statements. This has led to environmental impact statements where modeling was carried out with 100 to 200m mixing heights, while (as mentioned above) 10m would be more appropriate. One model--ACOSP (Norton and Carlson 1976, Carleton and Fox, 1976, Carlson and Hok, 1980) has been developed for the Fairbanks CO problem, but it has not been adequately tested, in part because meteorological input data were not available. In this respect it is significant that ACOSP's best reproduction of observed CO levels was obtained using a 10m mixing height--exactly the height we have since recommended on the basis of tethered balloon measurements.

CO Forecasting

The Fairbanks North Star Borough produces a regular CO forecast during the air pollution season (October - March). This forecast is based on a modified persistance forecast (today's forecast maximum 8-hour CO level = yesterday's 8-hour maximum times the ratio of the most recent 8-hour level available to that for the same time the previous day) which is then adjusted to account for a dispersion forecast issued by the National Weather Service. The resulting forecast improves on persistence, but has rarely been successful in forecasting CO levels above 15 ppm. Provision of CO data to the Weather Service has improved the dispersion forecasts given to the Borough, but severe problems remain, especially in forecasts of surface winds in the downtown area (Bowling, 1983).

Recommendations for Further Research

1. Probably the most pressing problem in the meteorology of high latitude air pollution is the verification, to standards that EPA will accept for environmental impact statements, of a dispersion model capable of handling high latitude meteorology. Two obvious candidates are ACOSP and a currently accepted Gaussian model with decoupled hori-

zontal and vertical dispersion. Verification would require several periods with good meteorological measurements (in-town soundings and/or tower measurements to at least 50 m, winds throughout the area) and either CO sources and concentrations or a tracer release. Fairbanks is the obvious site for initial verification, but once meteorological measurements are available from other areas (such as Anchorage) it might be possible to apply the model there as well.

2. Another area in which meteorological knowledge is seriously deficient is the variation of winds, temperatures, and lapse rates through the Anchorage area (needed for any detailed modeling there).

3. One problem for which no references were found for the bibliography is plume rise under stable conditions with significant winds and wind shears at some or all levels below the height to which the plume rises. The general problem involves both the fate of elevated plumes in interior Alaska and the behavior of plumes on the North Slope. In the Interior, a plume may rise through several layers with opposing wind directions before leveling off. Understanding of plume behavior is needed to evaluate the impact of such a plume on elevated terrain. On the North Slope, existing models may not be doing an adequate job of stimulating the rise of hot, high-volume plumes from short stacks, which may be associated with buildings on pilings. The combination of stability with high wind speed on the North Slope has scarcely been looked at.

4. Study of the synoptic situations most often responsible for high CO levels in Fairbanks. The goal here would be improvement of the existing CO forecasting scheme in Fairbanks.

5. The effect of wind shears on vertical dispersion. This is an extremely complicated micrometeorological problem which will be difficult and expensive to execute.

ICE FOG: A SPECIAL FORM OF COLD REGIONS AIR POLLUTION

The most startling, visible manifestation of urban winter pollution in the cold regions is ice fog. Although ice fog may occur in pristine areas, for example near hot springs, at very low temperatures, it is primarily an anthropogenic substance produced by the combustion of fuel in houses, power plants and automobiles. This combustion, whether of gasoline, fuel oil, coal, wood or other materials, produces water vapor which condenses into very small droplets and freezes at temperatures below about -30°C, on occasion reducing visibility in the city to as low as a few meters.

In combustion processes the primary exhaust products are H_2O and CO_2. As an example, consider an ideal combustion equation for gasoline:

	Molecular weight of fuels	Molecular weight ratios H_2O/fuel	CO_2/fuel
$C_8H_{18} \xrightarrow[\text{excess } O_2]{\text{burned with}} 8\ CO_2 + 9\ H_2O$	114	1.42	3.08
		Avg 1.38	3.10

This type of equation has been used to calculate the amount of water released in burning various types of fuels (Benson, 1965, 1970).
Although they yield order of magnitude values for the amounts of H_2O and CO_2 they are incorrect, especially at low temperatures and during "cold starts" of automobile engines. Cold starts produced large amounts of CO (Leonard, 1975, 1977), this fact and the presence of unburned hydocarbons (Jenkins et al., 1975), indicate that combustion is incomplete. The degree to which combustion is complete increases as the engine or burner warms up. The presence of high CO concentrations, the predominance of NO over NO_2, the lack of O_3 and the fact that the water which comprises

ice fog is basic (pH as high as 10) indicates a reducing atmosphere; this is an important aspect of low temperature air pollution, as already shown in a previous section.

Even with the above qualifications, it is clear that H_2O and CO_2 are the most abundant products of combustion. However, other sources than combustion roughly double the amount of H_2O added to the atmosphere. The largest of these other sources are the open water surfaces maintained by dumping of cooling waters from power plants (Benson, 1965, 1970, Ohtake, 1970, and McFadden, 1976). The rate of evaporation from warm water in cooling ponds is about 8 kg m^{-2} day^{-1}.

The Effect of Freezing on Fog Formation

When cooling occurs the air rapidly tends toward saturation (with respect to water). The cooling also stimulates increased input of water into the air from man-made sources. When the air is saturated, water vapor will be condensed in it as the temperature continues to decrease; at -35°C the rate of condensation will be 0.027 g m^{-3} $°C^{-1}$. Freezing of supercooled water droplets occurs at temperatures of about -35°C. This has the effect of reducing the saturation vapor density in the air because the vapor pressure must now be reckoned with respect to ice; at -35°C the difference between water vapor density relative to ice and water is 0.083 g m^{-3}. Thus, the effect of freezing of -35°C will force condensation of three times the amount of water forced by 1°C of cooling at -35°C.

The volume of air involved in the Fairbanks area is on the order of 2×10^9 m^3 so the freezing alone adds 160 metric tons of water to the air in a few hours as the cooling proceeds. For comparison, this is

about the same as the daily output of water vapor from the University of Alaska heating plant. Yet, this rapid addition is spread throughout the the entire area. The net result of rapid cooling, saturation of the air mass, freezing of droplets and continued - or accelerated - man-made input of water to the atmosphere, is an explosively rapid spread of thick ice fog at temperatures of -35° or below (Benson, 1965, 1970).

Mass Balance

The first attempt to estimate the mass balance of ice fog in the Fairbanks area was made by Benson (1965, 1970). The growth of Fairbanks since then has made it necessary to re-evaluate the mass balance. A preliminary attempt to do this during the winters of 1981-82 and 1982-83 indicated that the total rate of input of water to the Fairbanks air mass in winter is between 10,000 and 12,000 metric tons per day. Precipitation rates of ice fog particles have been measured to be as high as 80 g m^{-2} day^{-1} in the city center and 20 g m^{-2} day^{-1} in the outlying areas. If the core area is taken as 50 km^2 with an outer region of 100 km^2 and an outermost region of 100 km^2 we can calculate the total precipitation rate as follows:

Area km^2	Preciptation Rate g m^{-2} day^{-1}	Total Precipitation Rate(tons per day)
50	80	4000
100	50	5000
100	20	2000
	Total	11,000

Refinements are obviously in order because these values are based on very few measurements, but the agreement between total fallout and total input is close enough to indicate that we have the correct order of magnitudes (Benson, unpublished data).

The characteristics of ice fog are briefly summarized below:

Size Spectrum

The size spectrum of ice fog was studied intensively by Ohtake (1970). He found that the mean diameter decreased with decreasing temperature, from 33 μm at -30°C to 3 μm at -47°C. The source of water vapor was also a factor, probably due in large part to the temperature of the exhaust gases. Automobile traffic produced the smallest crystals and was accompanied by high concentrations of crystals smaller than 2.5 μm.

Residence Time

To calculate residence time we need the average vertical component of the settling speed for a wide spectrum of particle sizes. This can be obtained by dividing the precipitation rate by the solid water content of the atmosphere. First estimates (Benson, unpublished data) yield a range of 0.1 to 1.0 cm sec^{-1} for the range of vertical falling speeds. When considering that the thickness of ice fog ranges from 10 to 150 m we obtain residence times ranging from 1 to 14 hours.

Optical Effects

The small crystals in ice fog are often nearly spherical and always irregular in shape. They lack the well defined plate or needle shape of crystals which form in a gradually cooling air mass. The small sizes and irregular shapes explain the complete lack of reflection and refraction features in ice fog - indeed, its optical characteristics are more like a water droplet fog than a display of ice crystals (Benson, 1970, Bowling, 1970).

Thermal Effects

The cooling and crystallization of 12000 tons of water vapor per

day will add energy to the air at a rate of about 3.4×10^{10} k J day^{-1}. This is on the order of 4×10^{8} watts or about 2 W m^{-2} in the Fairbanks area. An exceptionally strong heat island results over the city (see also p. 13) but the effects of ice fog are to reduce the heat island for reasons which are not yet fully understand. The total heat output in the Fairbanks area during winter was calculated to be 10 kW per person (Bowling and Benson, 1978), or about 19 W m^{-2} (Benson, Bowling and Weller, 1983).

Removal of other Pollutants by Precipitation of Ice Fog

The effect of precipitation in general is to clean the air. There is some question about the ability of small ice fog crystals to remove pollutant particles which are larger than the ice crystals. Ohtake is currently investigating this. There are two facets to the problem: first the adhesion of particles to ice crystals and second the adsorption of gases on the ice crystals. The specific surface area of ice crystals in ice fog is on the order of 10,000 to 20,000 cm^2 per gram of ice. It seems reasonable that this large surface area would interact with other materials, particulate and gaseous, in the air. Furthermore, the ice fog residue which precipitates on clean surfaces is very dirty. It contains 0.5 - 1% of matter other than ice, has a foul odor and basic pH values, up to pH = 10.

Recommendations for Further Research

The ice fog represents the visible part of a concentrated air pollution setting which requires further study. So far, attention to ice fog has concentrated on visibility aspects of the problem. Because it is visible, ice fog serves as a tracer that indicates the presence of

other exhaust products. It must be remembered that water is a highly reactive substance which has complex physical, chemical and thermal effects on other components of the air mass, all of which need to be better understood.

1. The mass balance of ice fog needs reassessment in light of the greatly increased population and fuel consumption of Fairbanks and other northern cities where ice fog occurs.
2. The residence time of ice fog particles needs to be investigated under a variety of different meteorological regimes.
3. The likely physical-chemical reactions between ice fog, supercooled water droplets and other pollutants present must be better known, for example, does ammonia and HCN from motor vehicles with catalysts produce the high pH values of ice fog? Do ice fogs contain cyanide in Fairbanks and how much? How do solvents from dry cleaning establishments react with ice fog etc?
4. The possible scavenging of pollutants by ice fog particles, including selective chemical and physical interactions needs further investigations.

ARCTIC HAZE: LONG-RANGE TRANSPORT OF INDUSTRAL POLLUTANTS

Except for isolated areas of air pollution centered on inhabited communities dotting the Arctic, it has always seemed reasonable to suppose that Arctic air masses must possess extraordinary chemical purity. It wasn't until the late 1950's and early 60's, however, that serious analytical air chemistry was begun in the Arctic, mainly by Professor Junge in Germany. The first measurements indicated, to no one's surprise, that Arctic air and snow were very clean, but by employing sensitive analytical methods chemists identified the presence of trace pollution preserved in the snows of remote areas like northern Greenland (Herron et al., 1977). The contaminated ice extended to depths in the Greenland ice sheet corresponding to about the beginning of the industrial revolution. Thus, even though quantities were miniscule, traces of man's activity could be found preserved in the polar snows.

Most of the pioneering chemical work in the Arctic was carried out during summer expeditions, (e.g. Flyger, et al., 1976), but with the wisdom of hindsight this was a mistake: in summer, the air is about as clean as one can find anywhere on the planet, but in winter the Arctic air becomes infiltrated with air pollution.

In the early to mid seventies for example, routine investigations near Barrow, Alaska indicated that fairly substantial quantities of aerosol were present in the lowest 1 or 2 kilometers of the atmosphere during the late winter and early spring months, (Rahn and Heidam, 1981), a surprising finding since the mass loading of aerosols seemed to be greatest when winds came from the North! It was difficult to understand why the air appeared hazy when the number concentration of

suspended aerosols during haze episodes remained quite small, changing hardly at all from non-haze times. It is now realized that the ambiguity arose because the Arctic pollution aerosol has a size distribution differing from that encountered in urban situations: the Arctic aerosol does not have as many small particles (Shaw, 1983).

Because the aerosol associated with Arctic air masses lowers visibility, the phenomenon is termed "Arctic Haze". It is believed to be synonymous with the unexplained haze reported by observers who flew on the U.S. Air Force Ptarmigan Weather Reconnaissance missions out of Alaska in the middle 1950's (see Mitchell, 1957, for historical accounts and Raatz, 1983, for a more recent analysis of the Ptarmigan data).

The chemistry of "Arctic Haze" was investigated in the mid-1970's in Alaska, and in the Scandinavian (Ottar, 1981), and Canadian Arctic. Rahn (1981), started a systematic program collecting air samples at Barrow, Alaska. The sensitive neutron activation method was used to determine the chemistry of the haze particles. It rapidly became apparent that the haze at Barrow had an anthropogenic "fingerprint" and could therefore be considered to be a form of air pollution. Similar findings were made in Canada and Scandinavia (Barrie et al., 1981).

Efforts have been underway since the discovery of Arctic Haze to clarify the source regions and transport pathways of the pollution, but the work has been fraught with difficulty (Rahn and Shaw, 1982). Speaking of Arctic Haze in Alaska, one can easily eliminate eastern Asia as a major source of Arctic aerosol: air from the Pacific pathway is the

cleanest observed due to the extensive storminess along the route. Likely source regions were suspected to be eastern North America and Europe (including the western USSR). Attempts to be more specific by constructing back trajectories along the direction of the winds were not entirely successful (Miller, 1981), one reason being that trajectories calculated for the Arctic are less reliable than for other locations, and another being that small systematic errors pile up and limit what one can deduce about polluted air masses that have traveled for more than about three days.

Two significant advances in the origin and pathways of Arctic Haze were made in the early 1980's. Raatz (1983) analyzed synoptic weather patterns occurring during and before episodes of Arctic Haze at Barrow. By using an iterative "closure" approach, he was able to demonstrate that most strong episodes of haze in the Alaskan Arctic are preceded by surges of northward flowing air over polluted areas in eastern North America, Europe and the Soviet Union. The pollution-laden air travels in characteristic large scale anticyclonic air circulation patterns.

Rahn (1979), and Rahn and Lowenthal, (1984), took another approach: they investigated chemical signatures in air samples collected in the Arctic. Characteristic signatures of certain trace elements present in Arctic Haze seem to relate to specific, albeit large, geographical regions in which the pollution aerosol was injected initially into the atmosphere. An example is the ratio of masses of pollution-derived manganese to vanadium (Rahn, 1981). This ratio varies for pollution by-products in source regions in the eastern United States,

in Europe, Eastern Europe and the Soviet Union. Part of the reason for the variation in relative quantities of certain compounds pertains to the abundances of elements present in fuel which are burned. Another factor may be sociological in nature, reflecting variations in air pollution control strategies in the different countries, the relative amount of coal to oil burned, the number of automobiles per capita, etc. The central region of the Soviet Union, for instance, is a coal-based society with a heavy steel-processing industry, and apparently is bothered by considerable air pollution. The region is a heavy producer, relatively speaking, of submicron particles containing Mn, whereas the element vanadium is a common submicron aerosol found in effluents from industrial sources burning fuel oils. Since the United States is an oil-based society, the Mn/V ratio is larger in pollution by-products from the Soviet Union than it is from the United States. The example shows the principle on which characteristic chemical patterns can be used to deduce relative strengths and source regions of inflowing pollution to the Arctic.

Rahn and Raatz's deductions about the source regions for the Alaskan-sector Arctic Haze agree with each other rather well. Both investigators deduce that central Eurasia is the primary source region for Arctic Haze in Alaska during mid-winter, whereas European sources become more predominant in the spring. North American sources seem to be minor, contributing perhaps one-fifth of the Arctic Haze in Alaska (Shaw, 1982, and Raatz and Shaw, 1984). The same general picture seems to hold for the Canadian Arctic (Barrie et al., 1981).

In spring, 1983, Arctic Haze was explored with airborne sensors on flights conducted by the United States, West Germany and Norway. One

U.S. experiment involved a WP-3D Orion research aircraft owned by the National Oceanic and Atmospheric Administration, which flew out of Anchorage, Thule and Bodø, Norway (Hileman, 1983). The flights were made during late March and early April, because the Arctic Haze is thickest at that time of year. A research aircraft owned by the University of Washington also conducted flights at about the same time of year out of Point Barrow, Alaska. Preliminary reports on some of the airborne experiments were presented and discussed at a meeting arranged by the Max Planck Institute in West Germany in September, 1983. An upcoming issue of Geophysical Research Letters will report on results of the U.S. airborne experiments.

Thus far, the effects of Arctic Haze on the environment are virtually unknown. Preliminary calculations imply that the haze absorbs a substantial amount of incoming solar radiation in the spring months, thereby causing heating of the atmosphere (Rosen et al., 1981; Shaw and Stamnes, 1980, and Heintzenberg, 1982). But so far very few quantitative measurements have been made and little numerical modeling has been carried out to estimate the climatic impact of Arctic Haze.

It is expected that a great deal of new and important information pertaining to Arctic Haze will be reported at the Third Symposium on Arctic Air-Chemistry scheduled to be held at Toronto in May, 1984.

Recommendations for Further Research

The complex phenomenon of Arctic Haze is becoming of increasing importance because of the large potential impact it may have on climate and polar ecology. It is all the more urgent that the problem be put in correct scientific perspective because of the large geographic scales

involved and because we are speaking of a multinational, even multi-continental, sort of problem in which different countries are polluting each other's territory.

1. In the immediate future, there is a need for continued and even upgraded monitoring of the chemical composition of the haze at a variety of surface locations around the Arctic Basin. The chemical tracers should include elements that provide source-specific signatures (see the recent paper by Rahn and Lowenthal, 1984), and possible source-specific organic gases.
2. There is a vital need to understand better than we do now the physics of gas-to-particle nucleation and, more generally speaking, the physics of aerosol and gas evolution in the well aged polluted Arctic air masses.
3. There is a need to know the relative amounts of light absorbed and scattered by Arctic Haze and its microphysical and macrophysical properties. These data are needed for numerical models to estimate the climatic influence of the haze.
4. Further work is desirable to assess the possible ecological effects caused by acidic precipitation in the Arctic.

AUTOMOBILE EMISSIONS AND THEIR CONTROL

Motor vehicle emissions are primary contributors of carbon monoxide, hydrocarbon and nitrogen oxides in urban areas. The high levels of carbon monoxide found in the two main urban areas of Alaska, Anchorage and Fairbanks, often exceed the National Ambient Air Quality Standards. They are almost exclusively due to motor vehicles operating during wintertime conditions of subfreezing temperatures and persistent ground based inversions (Hoyles, 1980).

Since the inception of the Federal Motor Vehicle Control Program (FMVCP), auto manufacturers have been mandated to gradually reduce emissions 90% from a 1970 baseline. To verify these reductions, the Environmental Protection Agency performs a Federal Test Procedure (FTP) designed to simulate "typical" urban driving conditions on a dynamometer. Fuel economy is also measured. These tests are performed at 20-30°C (68-86°F). Researchers noted that emissions were greatest when the engine was at its lowest temperatures, i.e., the initial startup when choking action is typical (ADEC, 1979).

Subsequently, studies done at temperatures lower than 20-30°C (68-86°F) showed even more dramatic increases in emissions at the startup and continuing until choking action diminished and steady state engine operating temperature was reached. Fuel economy also suffered (Austin et al., 1983).

The State of Alaska has a particular interest in the "cold start phenomenon" because of its extended winters. Most low temperature tests were conducted at 20°F (~ -8°C), but the Alaska Department of Environmental Conservation undertook testing at 0°F (~ -18°C) in an attempt to be more representative of Alaskan conditions. Insignificant

incremental increases were noticed between 20°F and 0°F and the cost and effort of sustaining acceptable equipment operation and satisfactory vehicle response precluded further testing at 0°F. Therefore, all work done at 20°F is included in this section and is considered appropriate for arctic and subarctic conditions (Coutts, 1983). Furthermore, in Fairbanks 35-40% of vehicle operators utilize engine preheaters at -10°F or lower temperatures, mitigating the cold start effect (Gilmore, 1978).

As manufacturers introduced new emission control technology to reach statutory limits, researchers found that some devices performed better than others in reducing emissions at temperatures below 68-86°F. However, it is important to note that there is no requirement that emissions be reduced by 90% or any amount, outside of the FTP temperature range. Areas suffering from the effects of such lack of regulation are forced to examine other strategies that may reduce cold start CO emissions.

Methods such as alternate fuels, retrofit devices, preheaters and low temperature tune-ups were investigated in Alaska and elsewhere to determine their effectiveness. All show some potential, but only emission inspection and maintenance of vehicles is being pursued as a workable strategy by both Anchorage and Fairbanks. This should be considered as an addition to preheaters which are already in widespread use. Fuel injected vehicles generally have lower cold start emissions (Austin et al., 1983).

The Environmental Protection Agency has developed numerous analytical tools to assist non-attainment areas (of pollution standards) in characterizing their future ambient CO levels due to auto emissions.

Both the data base and the computer model, Mobile 2.5, had to be modified for use in Alaska (Verelli and Moyer, 1982). Data were culled from all of the subfreezing testing programs, to form a data set known as "low temperature emission factors", i.e., actual emissions measured from in-use vehicles in grams per mile. A modified version of the model, called AKMOBILE2.5, was developed that allowed use of local mileage accumulation rates, the disablement of certain temperature correction factors, and an internal restructuring of the model that allowed more accurate input of the emission factors (Austin et al., 1983). AKMOBILE2.5 predicted that attainment of the 8 hour CO standard would not be reached by the year 2000 without control strategies over and above the Federal Motor Vehicle Control Program, such as inspection/maintenance and a check for tampering with emission control devices. This provided a significantly more realistic but bleaker prediction than the unmodified model.

Researchers also further refined the process by splitting the emission factors into stationary and mobile portions to represent emissions from a vehicle that is idling for long times while warming up, as is typical in Alaska, and emissions from the vehicle while in motion and warmed up. It was found that this modification was only significant when the typical commuter trip length was greater than approximately 3.5 miles (Hoyles, 1980). Most trips in Fairbanks are not significantly in excess of that distance.

Recommendations for Further Research

1. Emission Control Devices

   The low temperature performance of future emissions control technology that may be under development is not known because the manufacturers

are not required to test prototypes (or production) vehicles at low temperatures and even if they did, they are not required to divulge the results. This hinders planning and prediction efforts. Existing devices need to be comprehensively examined to determine which devices malperform or perform less efficiently at low temperatures. Devices or procedures such as failed rubberized components, air pump bypass valves, and catalyst light-off time are examples.

2. Tune-up Deterioration Rates

After a tune-up, emissions are reduced, then gradually over time, emissions increase until they reach or exceed the levels immediately before the tune-up. This is known as the deterioration rate and is measured by EPA on an annual basis. Only very limited measurements have been made of this effect under low temperature conditions. It is currently assumed that deterioration is unaffected by ambient temperature.

3. Diesels

While low CO emitters, diesels emit particulates, nitrogen oxides, and unregulated pollutants such as formaldehydes and other aromatics. If diesel sales continue to increase, the effect on ambient air quality in Alaska needs to be assessed. The performance of diesel engines in arctic and sub-arctic climates also needs more documentation.

4. Alternate Fuels

The emissions and fuel economy performance of gaseous fuels and alcohol fuels, other than gasohol, have not been adequately evaluated at low temperatures. More extensive studies need to be done, assessing the startability, driveability and ice fog production of vehicles using such fuels.

5. Tampering, Fuel Switching and Contamination

Anchorage and Fairbanks experience a rate of tampering with emission control systems and contamination of unleaded fuel and improper nozzles that exceeds the national average. It is suspected that misfueling rates are also higher. Tampering with emission controls and using leaded instead of unleaded fuel causes increases in emissions. It is not known if this effect is exacerbated at low temperatures.

6. Engine Size Effects

Although a data base exists now, analyses need to be done to determine the effects on the amount of cold start emissions by engine displacement. It is theorized that smaller size engines contribute less cold start emissions and that the trend in recent years towards smaller engines should have contributed to lower ambient CO levels.

Changes to the Clean Air Act and/or EPA Regulations

A statutory change is needed to set standards for motor vehicles at low temperatures in order to facilitate attainment of the ambient CO standard in Alaska. At the very least, the 3.4 g/mi standard should not be rescinded as proposed, since the standard forces the use of emission control technology that happens to also reduce low temperature emissions. Another approach to pursue would be an administrative one whereby EPA could allow manufacturers to make certain calibration changes that may also result in reduction at low temperatures without having to undergo extensive prototype testing and durability runs.

MONITORING COLD REGIONS AIR POLLUTION

Long-term monitoring of air pollution and its effects occurs at several locations north of 60°N. Routine monitoring of precipitation chemistry, for example, takes place at least at five locations in northern Canada and one location in Alaska (APCD, 1979; NADP, 1983; Shewchuck, 1983). Other studies add some additional precipitation data, e.g., Galloway et al., (1982) for central Alaska. Most of the data from those stations show normal clean backgrounds. There is, however, some clear evidence for acid precipitation, the effects of which are not well understood at high latitudes.

Perhaps the largest number of articles pertaining to monitoring discuss the various trace elements derived from long range transport of particulate pollution (see Arctic Haze section, p. 25).

In monitoring urban air pollution one or more of seven chemical parameters are usually considered. Those parameters are, carbon monoxide, hydrocarbons, sulfur dioxide, particulates, nitrogen oxides, lead and ozone. Each of these parameters will be reviewed in the following paragraphs based on what is available in the literature on cold climates.

Carbon Monoxide. One of the largest bodies of literature on pollutants in cold regions deals with carbon monoxide in urban areas. There are two unique problems in cold regions which cause many (not all) urban areas to have frequent carbon monoxide violations. First is the frequent occurrence of stable inversions (see Meteorology section, p. 11). Second is that cold starts of automobile engines produce significantly higher CO levels than in more temperate latitudes. Federal regulations do not

mandate a low temperature standard (see Automobile Section, p. 31) for arctic and subarctic regions. Recent increased use of wood stoves also exacerbate the problem.

Areas such as the Prudhoe Bay oil fields also have inversions, but wind dispersion is so much greater that there is no indication of excessive carbon monoxide concentrations.

Hydrocarbons are not routinely monitored in northern urban areas since ozone standards are not exceeded. The few hydrocarbon tests in the past do not show any unusual concentrations. Non-methane hydrocarbons in the air of the Prudhoe Bay oil fields are also well below Class II limitations (Crow et al., 1981).

Sulfur Dioxide does not appear to pose a problem in the urban areas of Alaska because of the relatively low sulfur content of coal used, and because the power plant emissions are usually above the steep inversions. One occasionally comes across titles of articles such as "High winter concentrations of SO_2..." for arctic and subarctic regions (Rahn et al., 1980). The term "high" is relative, however, since the peak values ($\sim 5\ \mu g\ m^{-3}$ or ~ 0.002 ppm) are well below permissible levels. Part of the reason for finding these "high" values so far from sources is the significantly longer life time of species at low temperature and low light levels (e.g., Bottenhein and Strausz, 1980, and Rahn et al., 1980). The recent Canadian report by Shewchuck (1983), shows that less than one percent of SO_2 in Canada is generated in the Northern Arctic provinces.

Particulates Depending on one's point of view, particulate loading of the air in arctic and subarctic environments is either normal to astonishingly high. Within urban areas TSP (total suspended particulates)

loading of filters is normally very low. There are occasions where high values are encountered in the summer (at or above the secondary standard standard of 150 $\mu g\ m^{-3}$ in Alaska, but below the primary standard of 260 $\mu g\ m^{-3}$). The high values in summer are usually attributed to high winds picking up road and river bank dust. Recently, however, winter TSP, mainly fine particles, have been observed to be approaching the primary standard limit in Anchorage and Fairbanks, probably due to smoke from wood-burning stoves. The Mendenhall Valley in Juneau has exceeded primary standards, due entirely to woodsmoke (Cooper et al., 1983), and Whitehorse has exceeded national guidelines (McCandless, 1982).

Observations of particulate organic matter (POM) and graphitic carbon in remote arctic locations have shown that the loading of these materials is comparable to large metropolitan areas for some periods of the winter (Daisey et al., 1981; Reichart and Reidy, 1980). Usually, however, they are a factor of 3 to 10 lower.

Nitrogen Oxides are not found in substantial quantities in cold regions except during some periods of inversion trapping in urban areas, when they can exceed 1 ppm in any given hour (limit is 0.05 ppm) on an annual basis (Coutts, 1979; Holty, 1973). The unique aspect of nitrogen oxides in the cold regions is that the nitric oxide (NO) level equals and frequently exceeds the nitrogen dioxide (NO_2) concentration (Coutts, 1979). This is due to the low photochemical activity and virtual absence of ozone within the city. There are no standards for NO and the only known test of its toxicity on mice was inconclusive.

Lead concentrations in urban environments have been decreasing in

the cold regions due to the shift towards unleaded gasoline. Some violations (> 1.5 μg m^{-3}) occur irregularly during periods of strong inversion trapping (Winchester et al., 1967, Gosink, 1983). Its presence in aerosols in remote regions, along with other trace elements such as vanadium, is used as an indicator of long range transport of pollutants from lower latitudes. The argument about background concentrations of lead in the environment is not yet resolved (Patterson and Jaworowski et al., 1983).

Ozone is one of several compounds used to indicate the occurrence of photochemical activity. No violations of the suggested 120 ppb limit have been reported in cold regions. However, summer highs approach this level. There are no concomitant hydrocarbon and NO_x data. Concentrations of O_3 in the Prudhoe Bay oil production area are slightly higher in winter than in summer (the winter high is only about half of the recommended limit) (Crow et al, 1981). Winter ozone concentrations decrease to zero inside the pollution zone of urban areas (see comments in Chemistry section about photochemical activity, p. 7), but outside the urban area of Fairbanks they have been observed in the range of 60-80 ppb, probably due to stratospheric subsidence.

Gaps in the Technical Literature

Several large gaps, reflecting absence of information, are apparent. For example, there are no reports on any health monitoring activities to see if there are unique problems with air pollution in cold regions. A full suite of up-to-date pollution monitoring data for metropolitan and urban areas does not exist. No data are available for the vast Soviet sector of the arctic and subarctic regions.

While the number of reports on trace elements in air particulates in the Arctic is large, the number of elements covered is limited. Information about organic matter in the air in cold regions is also very limited. Acetate and formate data at least should become a part of the acid precipitation monitoring program. Maps of soils in Alaska showing their sensitivity to acid precipitation are not available as they are for a large portion of the lower 48 and recently for the Northwest Territories of Canada (Shewchuck, 1983).

Recommendations for Further Research

1. With regard to precipitation chemistry, trace element data for rain versus snow are needed. The information should also distinguish between wet and dry fallout and between soluble and insoluble forms of the elements.
2. Data on the size distribution, and composition of atmospheric pollutants (organic and inorganic compounds) in urban, rural and remote atmospheres are required.
3. The fate of elements and organics deposited on the surface needs to be known, and the quantity of organic matter re-emitted to the air in the same or modified form needs to be determined.
4. Deposition velocities on various surfaces, including plants, snow, ice and water etc., must be known.
5. The collection efficiency and best locations of wet and dry deposition collectors need to be determined. Furthermore, devices that will operate in cold environments need to be developed.
6. Oxidation rates (e.g., of NO and SO_2) under low light and low temperature conditions must be investigated.

SUMMARY OF RECOMMENDATIONS

Additional or new studies are required in the following areas, roughly listed under the various sub-headings in an order of priority which ranks the severity of present data and information gaps. This list is compiled regardless of the cost of the research involved or the relation of the recommended research to the missions of EPA or DOE in reducing pollution. Research priorities with such considerations in mind have been established only recently for EPA and DOE (States, 1983, see Preface).

Sources and Characteristics of Major Air Pollution Types

1. Full-year monitoring of the concentrations of the seven EPA priority pollutants in northern urban areas (pages 36-39).
2. Chemical composition of Arctic Haze (including source-specific chemical signatures).
3. Mass balance and physical-chemical characteristics of ice fog.

Chemical Processes and Conversions

1. Interactive processes between ice crystals, supercooled water droplets and other combustion products and pollutants.
   a) alkalinity of ice fog (ammonia, fly ash, acetate, formate)
   b) scavenging of pollutants such as PAH
2. Photochemistry at high latitude:
   a) ozone and PAN data for clean and dirty sites throughout the year
   b) data on hydroxy and peroxy free radicals
   c) oxidation rates (e.g., of NO and SO_2) under low light and low temperatures
3. Particulate matter:
   a) chemical fingerprinting (multivariate analysis) to determine sources.

b) rates of gas to particle nucleation (especially in dark atmospheres)

c) effects of selective partitioning on size ranges (relevant to respiration and health)

4. Precipitation chemistry:

a) rates and composition of wet and dry deposition (including snow and ice fog)

b) fate of materials deposited on surface (including re-emission of organic matter to atmosphere).

Dispersion and Transport of Pollutants

1. Dispersion model:

a) development and verification of a cold regions dispersion model.

b) data on winds, temperatures and lapse rates for input into model (particularly needed for Anchorage).

2. Vertical dispersion:

a) plume rise under stable conditions and effects of wind shears

b) scavenging efficiency of snow and ice fog

3. Meteorology of CO episodes:

synoptic situations responsible for such episodes.

4. Indoor air pollution:

transfer of pollution from the outside, trapping inside

Health and Other Effects

1. Eye and respiratory disease:

Statistical comparison between people in urban and rural areas

2. Acid precipitation:

   effects on arctic and subarctic ecosystems (including soil/vegetation susceptibilities)

3. Climate modification:

   effects of Arctic Haze on radiative transfer and climate

4. Carcinogenic factors:

   chemical and biological data of urban pollutants

5. Melt water pollution:

   chemical details of pollutants trapped in snow

Mitigative Measures and Controls

1. Automobile emissions and effectiveness of various control measures:
   a) emission control devices
   b) tune-up deterioration rates
   c) emissions from diesel engines
   d) use of alternate fuels
   e) effects of tampering and fuel switching
   f) effects of engine size
2. Wood smoke characteristics and control strategies

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  - In snow
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